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On-Site Laser Phonomicrosurgery – Challenges for an Endoscopic System Design with Integrated Augmented Reality

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Abstract

Current laser phonomicrosurgeries rely completely on the dexterity of the surgeons. Since the tissue manipulation and laser application requires a direct line of sight between the surgical microscope and the vocal folds, tilting back the patient's head might lead to a postoperative pain, i.e. for an elderly patient. Furthermore, the manual control of the laser is done via a mechanical micromanipulator mostly with a disadvantageous ergonomic setup.

In comparison to that, the µRALP on-site laser phonomicrosurgical approach targets the development of an endoscope containing all required technologies for an intervention in a more convenient position of the patient, without the need of a direct line of sight. Hence, tools currently inserted through a laryngoscope need to be integrated into the distal tip of the endoscope or be small enough to be passed through a work channel inside the device. A further challenge is the integration of the surgical laser into the endoscope requiring visual servoing based control of the laser spot. Due to the on-site limited control of the endoscope, an augmented reality system can support the surgeon by providing additional information through a live endoscopic video, pre-operative imaging and surgical planning.

During this talk, different types of endoscope kinematics are analyzed w.r.t. enabling high system integration and the appropriate degree of freedom for actuating of the distal tip. Recent approaches for endoscopic augmented reality are reviewed in order to determine their limitations and the expected challenges for on-site laser phonomicrosurgery.

Outline

- State of the Art – Laser Phonomicrosurgery
- Required Components for µRALP
- Actuated Distal Tips I
    - review
    - conclusion
- Integration of an Augmented Reality System II
    - various ideas for laryngeal imaging and planning
    - surface reconstruction as step towards augmented reality
    - recent approaches towards endoscopic augmented reality
    - conclusion

State of the Art – Laser Phonomicrosurgery

Surgical Procedure (engineer's point of view):

- manipulation of soft tissue with forceps
- aiming and adjusting with visible low power laser
- cutting with CO_2 – Laser

Advantages of the On-Site Approach:

- endoscope with integrated components
  - reduction of the working distance
  - patient can be treated in normal lying position
- supply of additional information
  - e.g. pre-operative data
- improvement of the cutting precision
- extended 3D endoscopic vision

Laser Phonomicrosurgery, UHG Besançon

[Giorgio Peretti, UNIGE]

Required Components: Conventional vs. On-Site

Component	Conventional	On-Site
main tool	laryngoscope	mechatronic endoscope
vision	stereo microscope	stereo camera setup
light	external lamp on laryngoscope	integrated light fibers
laser beam exit point	outside the patient	inside the patient
laser control	manual micromanipulator	micro robot with visual servoing closed-loop control (requires two high-speed cameras)
tissue manipulation	rigid forceps (through laryngoscope)	flexible forceps (through work channel)
lens Cleaning	-	water nozzle and suction
additional technologies	-	narrow band imaging auto-fluorescence

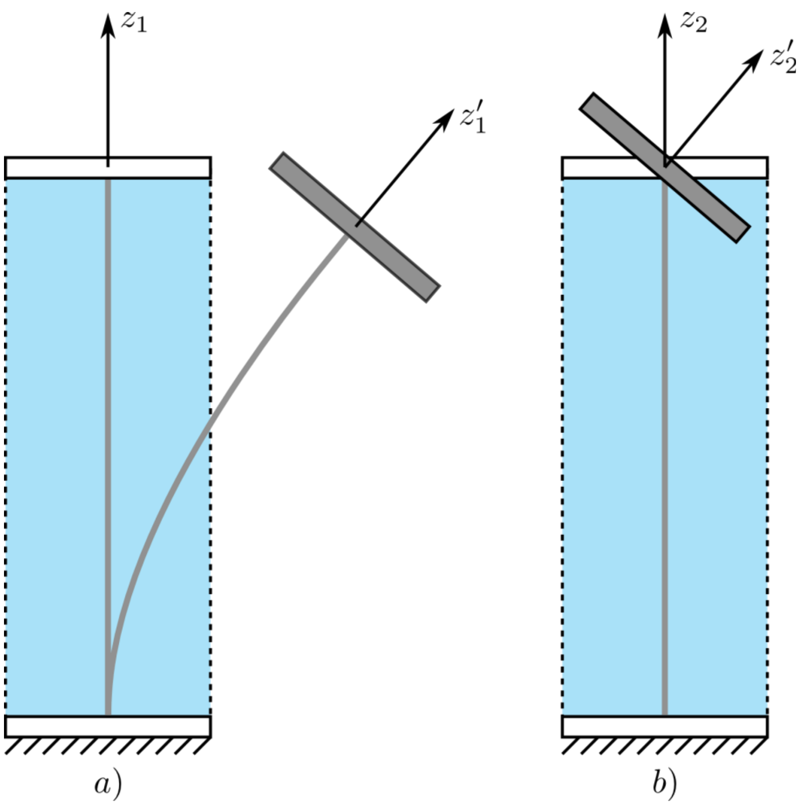
Actuated Endoscope vs. Actuated Distal Tip

a) Actuated Endoscope (snake-like endorobot)

- bending of the whole body
- combined rotation and translation
- often flexible shaft

b) Actuated Distal Tip

- rotation of the tip (sometimes with small displacement)
- rigid shaft – higher stiffness
- easier to control



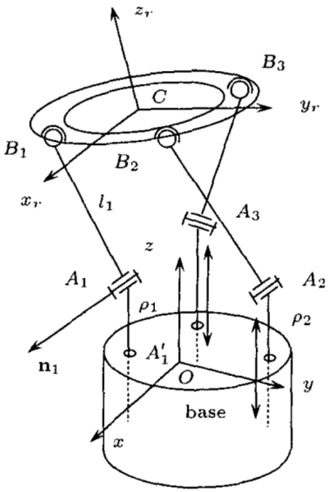
Concepts for Actuated Distal Tips I

- MIPS [Merlet (2001)]
- parallel kinematics

- 1 DoF linear (6 mm), 2 DoF angular (± 15°)
- Ø 7 mm, length: 25 mm

- screw drive (motors inside endoscope)
- able to exert a equivalent force of 15 g

- position sensors
  - differential variable reluctance transducer
  - length: 6 mm
  - resolution: 0.06 µm



[Merlet (2001)]

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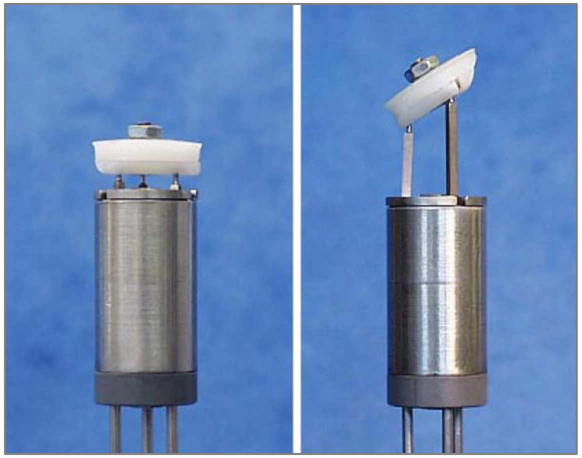
Concepts for Actuated Distal Tips II

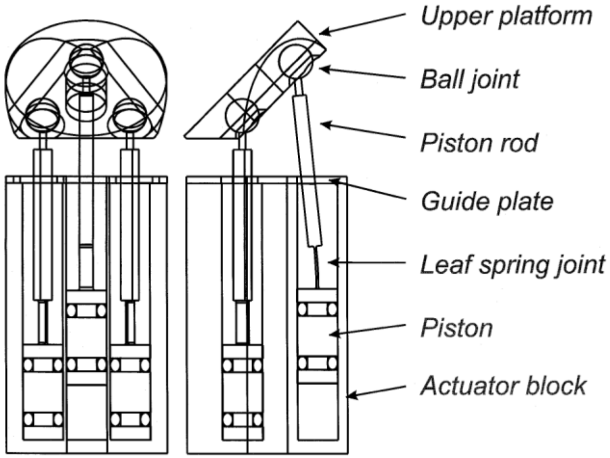
- Miniature manipulator [Peirs et al. (2001)]
- parallel kinematics

- 1 DoF linear (10 mm), 2 DoF angular (30-35°)
- Ø 12 mm, length: 30 mm

- hydraulic manipulator
- 4 pistons are needed for 3 DoF
  - 3 pushing / 1 pulling
  - force: 3.5 N per leg / 10 N in total at 10 bar

- pros and cons
  - \+ high stiffness and small size
  - – no space for cables and tubes inside tool





[Peirs et al. (2001)]

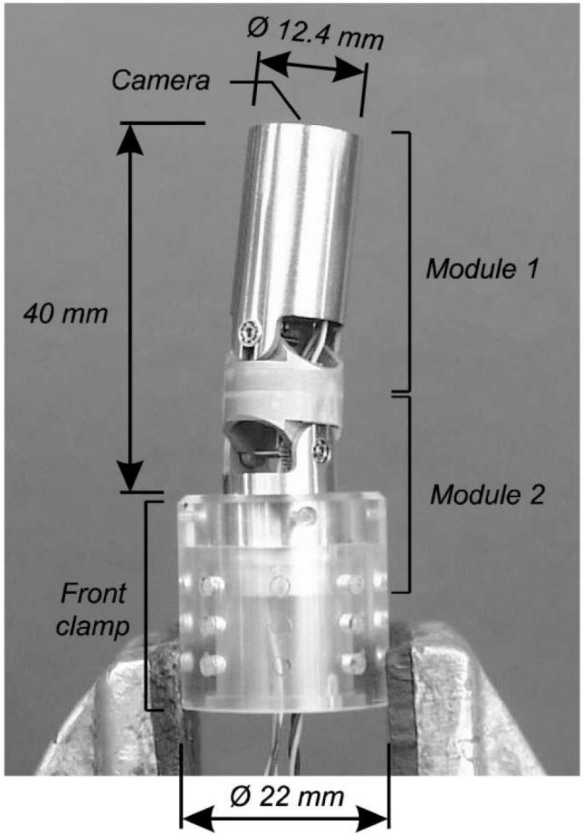
Concepts for Actuated Distal Tips III

- miniature manipulator [Peirs et al. (2000)]
- serial kinematics (module based)

- 1 DoF angular (± 40°) per module
- Ø 12.4 mm, length: 20 mm

- electromagnetic motor with attached worm gear

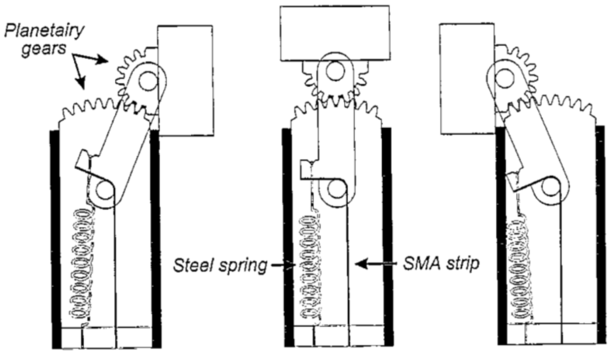
- pros and cons
  + small size
  + module based
  – only 1 DoF per module
  – displacement of distal tip
  – safety



[Peirs et al. (2000)]

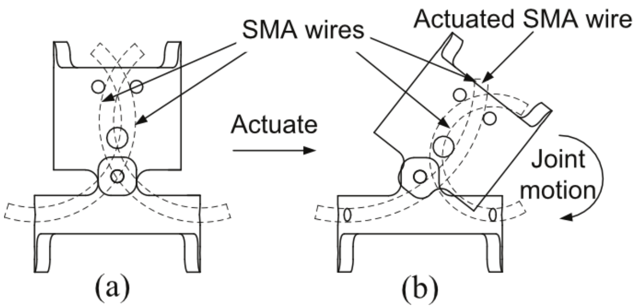
Actuated Distal Tips based on Shape Memory Alloy

- actuated endoscopic tip [Peirs et al. (1998)]
- pros and cons
  + very large stroke of ± 90°
  + Ø 6 mm
  – fine mechanics necessary
  – flexible in one direction



[Peirs et al. (1998)]

- serial kinematics [Ho et al. (2010)]
- pros and cons
  + stroke of ± 35°
  + module based
  + simple actuation
  – low precision and stiffness



[Ho et al. (2010)]

Conclusions

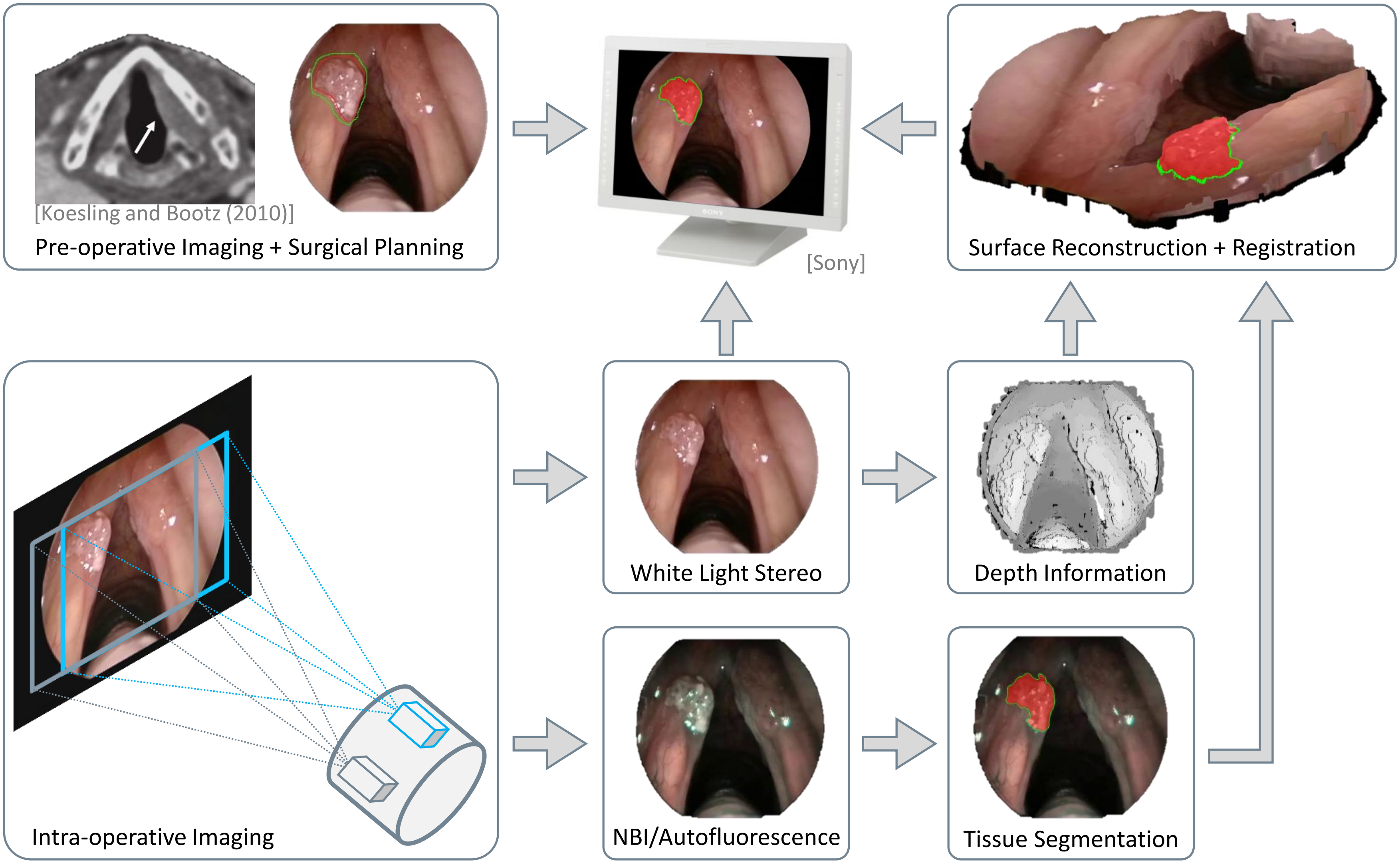
- parallel robots are commonly used for distal tip actuation
  - no / small displacement of distal tip
  - high stiffness and precision

- various actuation principles are utilized
  - screw drive, hydraulics, pneumatics, shape memory allow

µRALP Requirements for actuated distal tip

- small displacement of distal tip
- high stiffness (in order to allow accurate laser cutting)
- much space for cables, tubes, image, and light fibers
- as few mechanical parts as possible
- rotational workspace ± 20°

Integration of an Augmented Reality System



raw endoscopic vocal fold images from: http://www.giorgioperetti.it/ita/tecniche_chirurgia.htm. 11th June 2012.

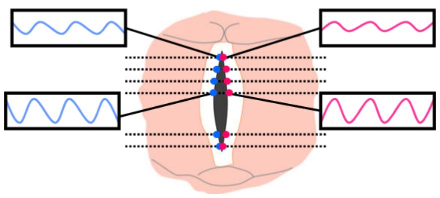
Various Ideas for Laryngeal Imaging and Planning

Pre-operatively

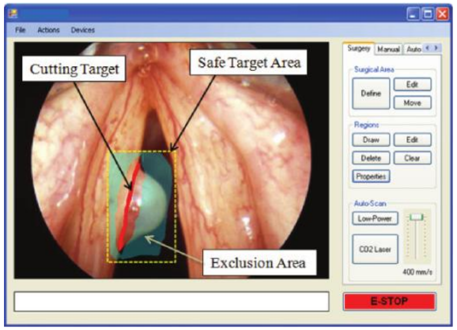
- conventional: laryngoscopy and CT / MRI
- high-speed videoendoscopy for functional evaluation [Ishii et al. (2011)][Skalski et al. (2008)]
- CT/MRI providing virtual laryngoscopy [Chen et al. (1999)]

Intra-operatively

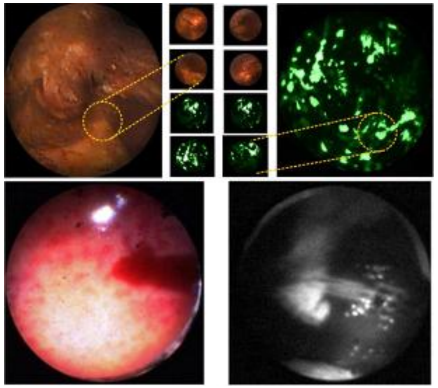
- concept of a virtual scalpel [Mattos et al. (2011)]
- applicability of optical medical imaging
  – *in vivo* tissue imaging [Noonan et al. (2009a)]



[Ishii et al. (2011)]



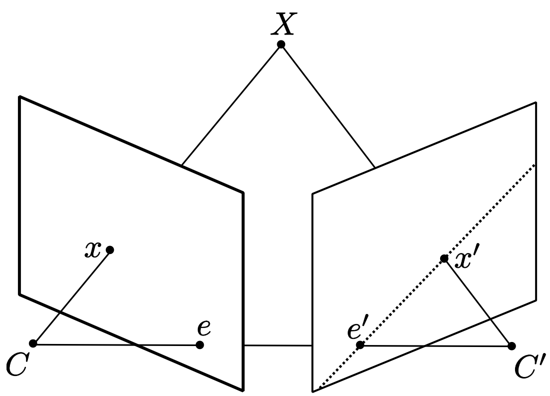
[Mattos et al. (2011)]

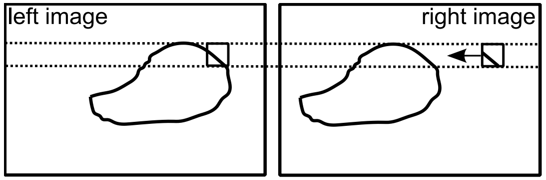


[Noonan et al. (2009)]

Surface Reconstruction as Step Towards Augmented Reality

- miniaturized stereo camera setup
- camera calibration [Zhang (2000)]
- image rectification [Hartley (1999)] [Fusiello et al. (2000)]
- area-based matching methods [Banks et al. (1997)]
  - SAD, SSD, NCC, rank, and census transform
- speeded up by integral images [Veksler (2003)]
- semi-global matching (SGM) [Hirschmüller (2008)]
  - 1 – 2 fps
  - GPU (13 fps) [Ernst and Hirschmüller (2008)]
  - FPGA (30 fps) [Banz et al. (2010)]
- triangulation for estimating 3D position

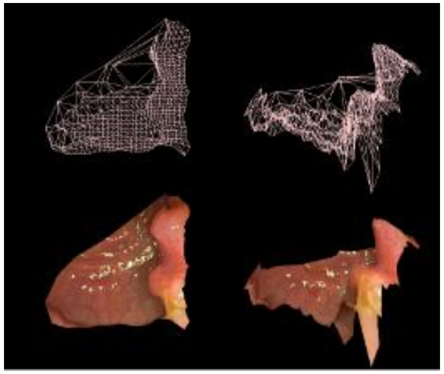




Recent Approaches towards Endoscopic Augmented Reality

3D endoscopy [Thormaehlen et al. (2002)]

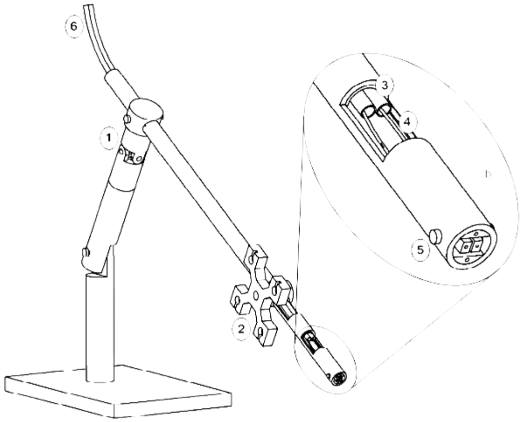
- motion estimation of monocamera and surface reconstruction from image sequences
- NCC with Harris features



[Thormaehlen et al. (2002)]

Stereoscopic fibroscope for MIS [Noonan et al. (2009b)]

- NCC with sparse feature map (DoG)
- optical tracking and CT scanning for ground truth
- challenges: specular highlights, feature tracking, tissue deformation, camera resolution, and baseline



[Noonan et al. (2009b)]

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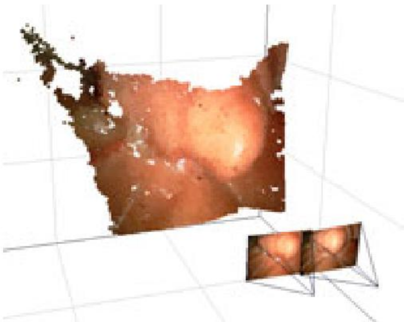
Recent Approaches towards Endoscopic Augmented Reality

Real-time stereo reconstruction for MIS [Stoyanov et al. (2010)]

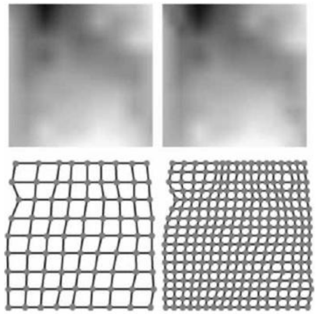
- coarse-to-fine: propagating sparse depth map (features, NCC)
- challenges: tissue deformation, occlusions, instruments, specular highlights



[Stoyanov et al. (2010)]

3D depth for robotic laparoscopic surgery [Stoyanov et al. (2005)]

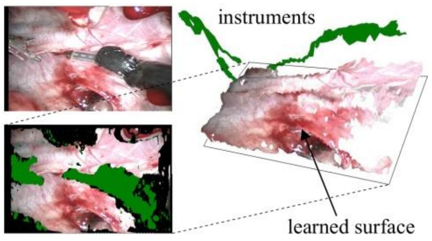
- NCC for dense depth map
- tissue deformation ➔ free-form registration [Veeser et al. (2001)]
- CT scan of tissue phantom for ground truth
- challenges: tissue deformation and specular highlight correction



[Stoyanov et al. (2005)]

surface reconstruction for image overlay [Mourgues et al. (2001)]

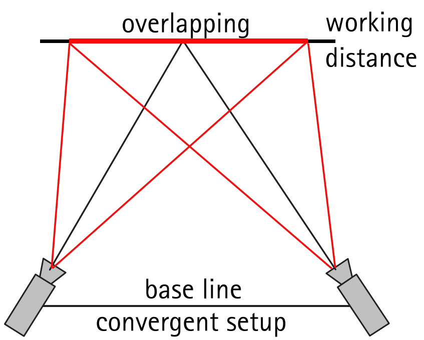
- 3D integration of pre-operative model by augmented reality
- correlation-based surface reconstruction as pre-step
- challenge: removing instruments by foreground and background classification (learning of z-statistics)

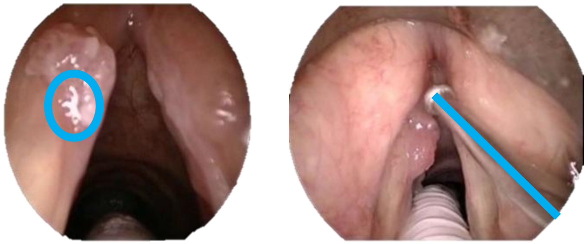


[Mourgues et al. (2001)]

Conclusion for Endoscopic Augmented Reality

- optimal setup for stereo-endoscopy
- applicability of NBI and fluorescence imaging for intraoperative tumor segmentation
- surface reconstruction in real-time
- tracking of
  - instruments and occlusions [Mourgues et al. (2001)]
  - specular highlights
    [Groeger et al. (2001)], [Stoyanov and Yang (2005)]
- tracking of tissue deformation [Veeser et al. (2001)]





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